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Doppler Direction Finder with Improved Characteristics

Starting in the late 1970s in the USA and the early 1980s in Germany, ideas were published for a simple direction finding system using the Doppler principle, which looked affordable by amateurs. As examples we can take the work of Rogers (3) and Zopp (4). In the USA indeed corresponding firms were established - for example Doppler Systems (6) - which produced direction finding systems of this kind for their special circle of customers. Somewhat previously manufacturers of RF apparatus had already started to use the Doppler system commercially for direction finding, for example the Bendix Corporation in the USA and Rohde & Schwarz in Germany.

I first became interested in these system in 1986 because they could be employed successfully in wildlife research. Price in this connection is extremely important, because research into biology or ethology doesn't attract defence sector-type budgets!

So we were looking for a low cost solution, closer to the amateur kind than a high-end product. Familiarity with amateur hardware revealed so many inadequacies in this apparatus that it seemed worthwhile studying the basic principles and developing a new concept. Meanwhile a new system of wild animal study was ready to put into service; details can be read in reference (1). The system is not immediately suitable for use in the amateur field. All the same, the principles used are identical so the following are some suggestions which could lead to an amateur Doppler direction finder which works well with high accuracy.

The details following assume that the reader has a basic understanding of how Doppler direction finding works and has perhaps read the publications of Rogers (3) and Zopp (4) or has even built a Doppler of this kind. Here I will restrict myself to questions handled too briefly in the named publications and that are critical to good operation. So we'll be dismissing the

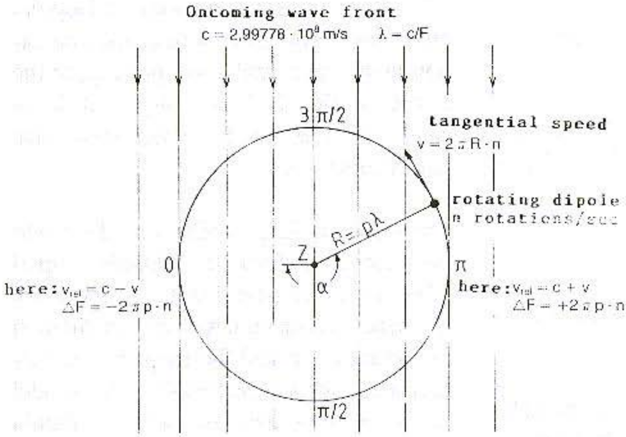


Fig.1: The conventional but technically incorrect deviation of the Doppler effect from the rotation of a dipole in a homegenous electromagnetic field

frequently cited theory of the rotating dipole and presenting what really goes on; we'll report on the nasty habits of commutators and indicate a better method; finally mentioning the requirements placed on the IF amplifier and oscillator of the receiver as well as the filtering of the Doppler signal following demodulation. Physics and mathematics cannot be kept out of this entirely; some figures will give a clue to the orders of magnitude to be expected.

1. THE ROTATING DIPOLE

In figure 1 a dipole is sketched, whose long axis is in line with the E-plane of an oncoming wave (vertical to the page in this illustration). In the H-plane it rotates around a central point Z. The radius of the circle of rotation is given as a multiple p of the wavelength. Equivalent or similar drawings are also found in Rogers (3) and Zopp (4) to illustrate that the speed relationship between dipole and wave on the left-hand side ($\alpha = 0$) is smaller and on the right-hand side ($\alpha = \pi$) than with a dipole at rest or in the upper or lower position ($\alpha = \pi/2; 3\pi/2$). Simple consideration brings us to the resulting Doppler frequency deviation

$$\Delta F = \pm \frac{2\pi \cdot R \cdot n \cdot F}{c} = \pm 2 \cdot \pi \cdot p \cdot n \qquad (1)$$

The form of this deviation is a sine wave, requiring no further explanation. Had we been concerned with waves that propagate themselves relatively slowly, e.g. sound waves - with which Christian Doppler (1803-1853) made the discover that is named after him - then there would be nothing more to say. But we are working with electromagnetic waves which propagate at the speed of light. And for this the "principle of the constancy of the speed of light" is valid, as discovered by Albert Einstein (1879-1955). Even if you don't remember much of the theory of relativity from your schooldays, the rule that you cannot exceed the speed of light may stand out still. Yet that's what we have assumed in Fig.1 by taking $\alpha = 3\pi/2$.

The correct evaluation can be sought following the rules of relativity set out by

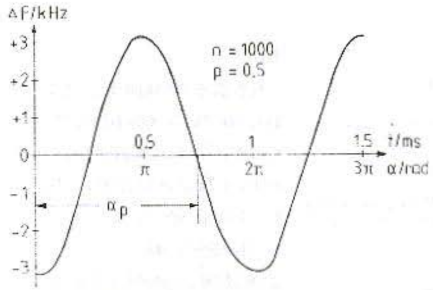


Fig.2: The Doppler frequency of a rotating dipole

Henrik Antoon Lorentz (1853-1928) in his transformation, which demands a lengthy demonstration which I'll do without here. In any case, it comes to the same solution as in equation (1) apart from a correction factor $\sqrt{(1-v^2/c^2)}$. The correction factor is in the realms of parts per million if one assumes v in technical reality around 10^3 m/s, whilst thanks to nature being in a good mood, c amounts almost exactly to $3 \cdot 10^8$ m/s. Anyone possessing a pocket calculator with sufficient decimal places can reach back to the measurements of Albert Abraham Michelson (1853-1931) and his students, who got $2.99778 \cdot 10^8$

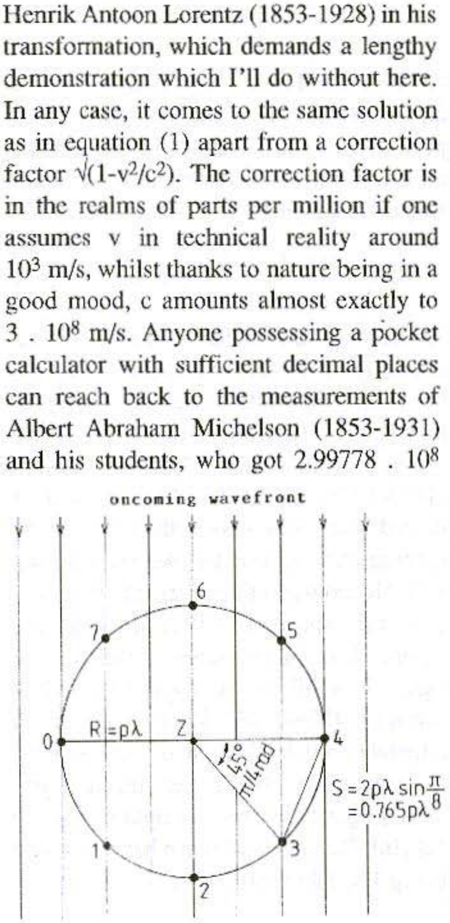


Fig.3: Arrangement of eight antennas in a circular group

m/s. There is also a transversal Doppler effect, which produces a frequency deviation in the upper and lower position of the dipole of fig. 1. This component is so small, however, that it can remain outside our calculations.

This excursion into physics should serve to find out what form the Doppler signal takes. We know now that it is a sine-wave frequency modulation with the modulation frequency f = n and the frequency deviation according to equation (1) if the model of fig. 1 is usable. An example should make the matter clearer. With n = 100Hz and p = 0.5 ΔF = 3142Hz. This function is drawn in fig. 2.

Direction finding of the azimuth α_p, of the angle between the null direction ($\alpha = 0$) and the direction of the oncoming wave is found by measuring the time or the angle of the null respectively reference point until the Doppler signal passes through zero and becomes negative in value. Developed systems of a simple kind according to references (3), (4) and (6) are certainly far removed from this model; more complex systems such as Rohde & Schwarz (5) differ significantly too. This is because the rotating dipole is replaced by a circular group of antennas which are scanned in rotation.

2. THE SCANNED CIRCULAR GROUP

Receiving dipoles set up at random in a field where waves are passing will deliver sine-wave voltages of a frequency $F = c/\lambda$.

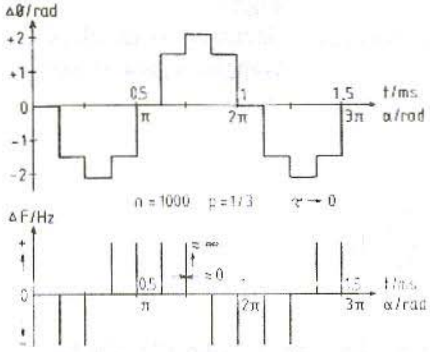


Fig.4: Phase deviation (a) and frequency deviation (b) of a circular group being scanned by rapid switching

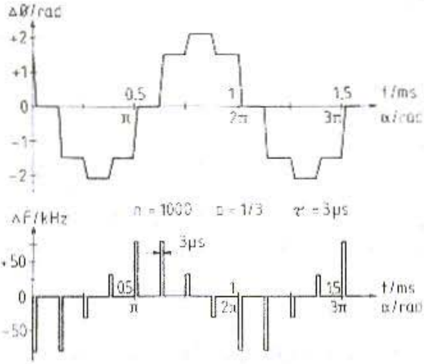


Fig.5: Phase deviation (a) and frequency deviation (b) of a circular group being scanned by unabrupt switching.

If we scan a number of them sequentially no kind of change in frequency can be detected. All the same, there is a change of phase generally occurs in the switch-over interval. If we take two dipoles erected in the direction of radiation a multiple of the wavelength apart, their output signal will exhibit not only the same frequency but also the same phase. If we want to detect phase relationships in an unambiguous fashion, we must restrain the separation range of our antenna layout to less than a wavelength, which means p<0.5. After this, the behaviour of the scanned antenna group changes fundamentally from that of a single antenna moved around. It is questionable whether the phenomena that occur then can even be called the Doppler effect.

Fig.3 shows a circular group of eight antennas. This figure was optimal for my application and would also be no bad choice for the radio amateur. It is better than a primitive system of four antennas and far less trouble than a large-scale set-up as described in (5). If we select p = 1/3, the phase deviation curve becomes a staircase as in fig. 4a. This presupposes that switching between the antennas is as fast as we want, which can be achieved closely by using switching diodes such as BA244 for approx. 10ns switching times. The advantage of these diodes is their extraordinarily low insertion loss at 50 ohms - one achieves values below 0.05dB. The frequency deviation is the differential quotient of the phase deviation

$$\triangle F = \frac{1}{2\pi} \cdot \frac{d\Phi}{dt} \qquad (2)$$

and is illustrated in fig. 4b. Entirely expectedly, it takes the form of needle pulses of the greatest size and disappearing widths (Dirac pulses). A discriminator for evaluating frequency modulation of this kind must be extremely broadband, even in the situation where an integrator is connected afterwards to maintain the staircase-form $\Delta\phi$ curve. Comparing Fig.2 with fig. 4a, an approximate phase shift of $\pi/2$

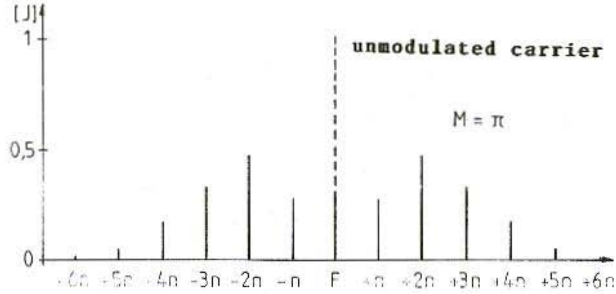


Fig.6: Spectrum of an ideal Doppler signal accoring to Fig.2

appears between the ΔF curve of the rotating dipole and the Δϕ curve of the scanned circular group. If the same phenomenon is affecting both signals, that is exactly what we would expect from equation (2). To begin with, we cannot get anything from the ΔF curve of the scanned circular group. The assumption is that the sum of all the levels encompassed by the Dirac pulses coincide with the levels below the curve of Fig.2. But ∝ . 0 can eventually produce every value! If we demodulate with an extremely broad FM demodulator (using a deviation meter with a linear region of plus or minus 500 kHz for example) and afterwards connect a bandpass filter for the frequency of rotation, then in fact we can measure a deviation of plus or minus 2000 Hz or so, which agrees with equation (1) and $p = 1/3$. Is this a Doppler effect then?

The ΔF curve from fig. 4b cannot be handled with narrowband receivers, also it is totally impossible to determine the point of passing through zero into the negative direction. The reason is the narrowness and height of the pulses, which must have something to do with the switching time of the switching diodes.

There is some benefit in slower switching times. Suppose we take PIN diodes, as used in all the instruments of (3), (4), (5) and (6). The resulting curves for ΔF and Δϕ are seen in Fig.5. The resulting signal can be processed in an broadband FM receiver - no solution for the radio amateur. A narrowband receiver would suppress significant components of the resulting spectrum, bringing in a reduction of and distortion to the deviation. The direction finding result would be unsatisfactory and dependent on the fortuitous position of individual spectral lines in the throughpass region and on the edges of the selectivity curve because, and this holds for all FM channels, linear distortion at IF level brings about non-linear distortion at audio frequencies. Despite this, a kind of Doppler effect is produced, otherwise instruments like (3), (4) and (6) would be totally unable to work.

3. THE DOPPLER SPECTRUM

It is easy to indicate the spectrum of an ideal signal as in Fig.2. If the measurements can be maintained in the same relationship to the wavelength, then the deviation of the Doppler frequency is

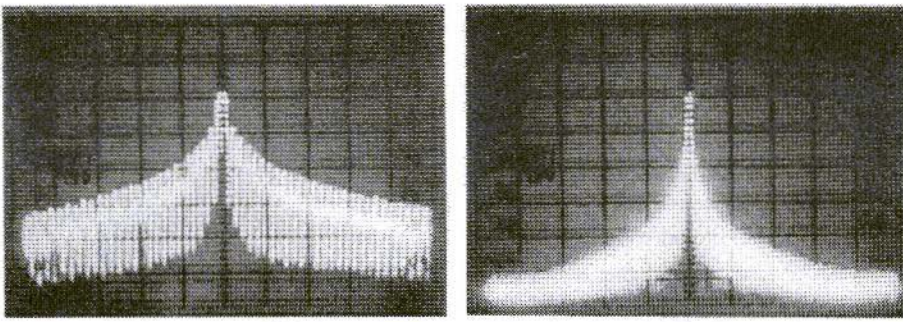


Fig.7: Spectrum of the 'Doppler signal' of the circular group scanned with a PIN diode
a. X: 20kHz per division. Derivation time = 5 seconds. Bandwidth analysed = 1 kHz. Video filter 1 kHz
b. X: 200 kHz per division. Derivation time = 5 seconds. Bandwidth analysed = 10 kHz. Video filter 1 kHz
Y is 10dB per division in both pictures

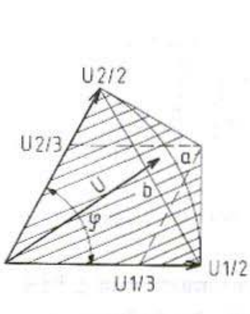
dependent only on the rotational frequency n. The modulation index resulting is thus

$$M = 2 . \pi . p \qquad (3)$$

r for the value of p shown in fig. 2 equal to π. We are dealing with broadband FM ($M>1$) then for as long as $p>1/2\,\pi = 0.159$. Calculation of the lines of the spectrum is carried out in the customary way with the help of Bessel functions and is demonstrated for $M = \pi$ in Fig.6.

Commonplace IF filters in amateur telephony receivers have a bandwidth of plus/minus 6 kHz. The spectrum of Fig.6 is valid as long as n does not exceed 1000 Hz, leaving even 1 kHz in reserve for mistuning. This is only one criterion for the selection of n; we will meet others later.

For the best results the IF filter should be optimised for flat transit time, for transit time distortion can also lead to non- linear distortion in the demodulated Doppler



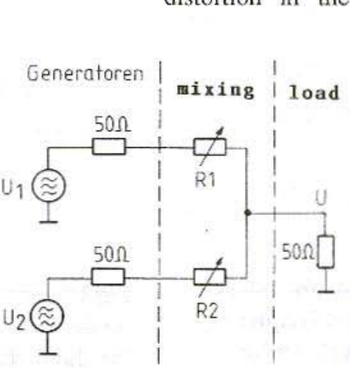


Fig.8: Mixing two generators with the same frequency but different phase

signal. They cause tuning-related variations in the bearing value, increasing with n^2. If variations of the bearing indication are established with only slight mistuning, then a lower value of n must be chosen or else a more suitable filter should be used. It often helps to improve the input and output termination of the filter already installed.

Instead of calculating the signal spectrum from scanning a circular group, which is not possible with precision on account of the unknown actual switching performance of the PIN diodes used, we show in Fig.7 properly measured spectra. The frequency scale in both illustrations is not suited for resolving a Doppler signal. On the other hand, they show that a very broad spectrum is produced which is fully demonstrable at an interval of plus/minus 1 MHz. That would not be bad if at the receiver input there was really only one frequency on hand whose source we wanted to home in on. Fig. 7a shows that 90 per cent of the energy of the spectrum lies within plus/minus 7 kHz and 99% of this energy is within plus/minus 25 kHz. Both values are sufficient for establishing a close approximation of the Doppler frequency deviation, naturally better in the second case than in the first. This explains the method of operation of the instruments of (3), (4) and (6).

In practice, the antenna group picks up a quantity of other transmitters whose frequencies can differ either a little (e.g. 20 kHz) or a lot (several MHz) from the frequency in question. All are provided with a spectrum as in Fig.7 by the PIN diode commutator. Resulting sidelines will fall within the channel under investigation and will produce interference. The receiver, which previously exhibited 80dB selectivity against neighbouring channels, now shows only 18dB (Fig7a). Strong

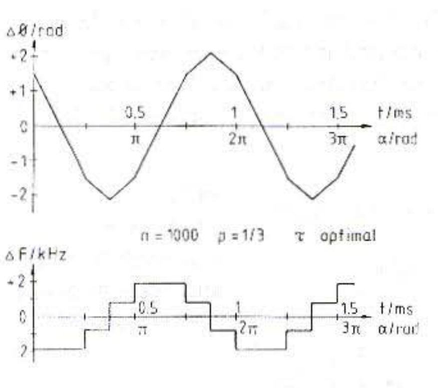


Fig.9: Best curve forms for phase deviation (a) and frequency deviation (b) that can be achieved by optimised mixing

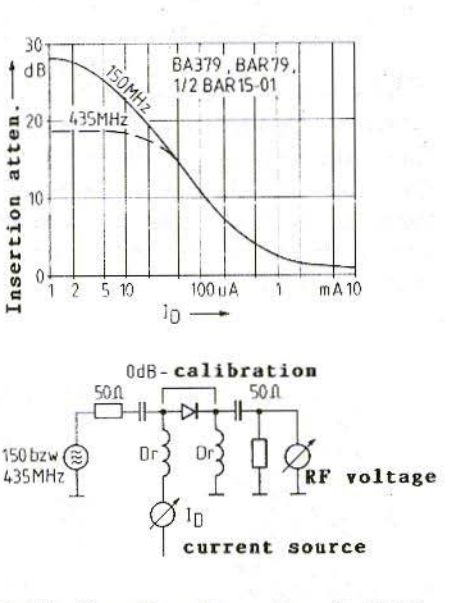


Fig.10: Insertion attenuation of a PIN diode switch showing dependency to the diode direct current: measurement circuit

out-of-band transmitters (aeronautical, PMR, etc.) will overpower weak desired signals. In short, the receiver has to a large extent lost its characteristic of suppressing unwanted signals. This is the actual reason why instruments working in this fashion cannot give satisfactory results.

In fact it is superfluous to say that apparatus of type (5) are free of the effects described. For most radio amateurs, however, it is only affordable when it turns up surplus or at a flea market. People who are not prepared to wait, or want to build their own or else would like to "supercharge" their existing inadequate Doppler equipment should read on.

Anyone who can afford high-end equipment will find plenty to read in Grabau and Pfaff (2), covering among other things bearing errors in multiple reception, determining the elevation of the incoming wave and complex evaluation techniques. This book appears to me to be the most recent pronouncement on the state of this technology. Here I just want to go as far as achieving the best Doppler signal with the least effort.

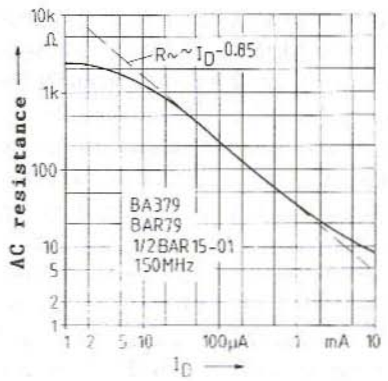


Fig.11: AC resistance of a PIN diode switch showing dependency to the diode direct current

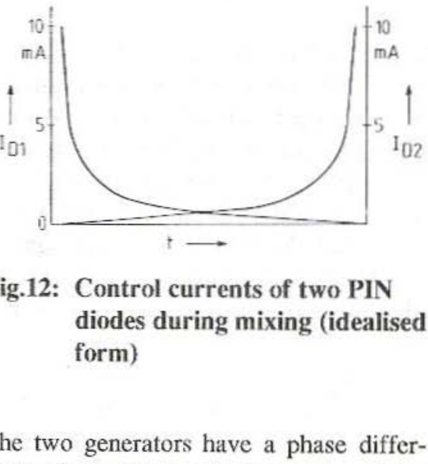


Fig.12: Control currents of two PIN diodes during mixing (idealised form)

4. THE RIGHT COMMUTATOR

That actual switching between antennas should not be allowed should now have become clear. The problem of achieving a signal transition between antennas such that the ΔF curve comes out as in Fig.2 can be reduced by mixing a generator with another of the same frequency but different phase. We can examine this in fig. 8.

The two generators have a phase difference of φ. After adjusting each of the mixing controls R1 and R2, all values of the resulting output voltage u can be confined within the shaded zone in the diagram. That gives us the opportunity of leading the end of vector u (arrowhead) along any desired path from $u_1/2$ to $u_2/2$. The end of the mixing process is reached each time that R1 = 0 and R2 = infinity (and vice versa). Two clearly special paths of the arrowhead are useful: with one, the

value of the vector remains constant and the route is an arc of a circle. In the other, the source resistance, which the load sees, remains constant; this path is a straight line between the end points. Whilst the arc, using this dissipative (lossy) mixing arrangement, can no longer be achieved above a certain value of angle φ, the second way is always feasible. It does of course produce an amplitude modulation component, to be eliminated in the receiver, but has the advantage of a match that remains constant, which a high performance input amplifier in a receiver likes to see. The following relationship is maintained then:

$$R1 \,.\, R2 = (50\Omega)^2 \qquad (4)$$

In themselves, R1 and R2 could be replaced by active elements whose amplification could be altered in similar fashion. Passive modulators might be suitable too. However, in the PIN diode we have already a building block whose RF resistance over the DC flowing through is variable over a wide range. It introduces no additional distortion above a certain frequency (about 40 MHz here) and is available with sufficiently small tolerances. If we give the control currents of the PIN diodes suitable time functions, we can then by means of these phase manipulations imitate the rotating dipole of Fig.1 so far as to make it appear to be moved through an octagon. The best achievable curve forms for $\Delta\phi$ and ΔF in this way that can be expected are illustrated in fig. 9.

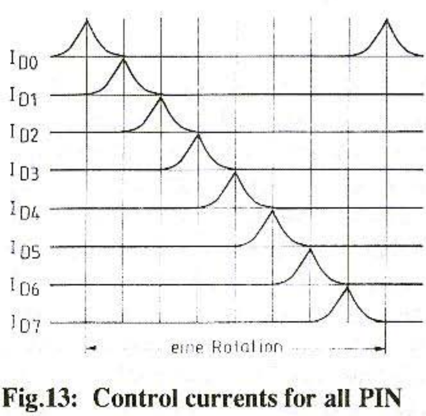


Fig.13: Control currents for all PIN diodes during a rotation in the mathematically positive sense

So that the amplitude modulation does not become too great, the phase differences between the RF voltages of neighbouring dipoles should not get too large. The greatest variation occurs when the wavefront comes in rotated by 22.5 degrees as against to Fig.3; it is then

$$s = 2 \,.\, p \,.\, \lambda \sin \pi/8 = 0.765\, p\lambda$$

Should φ remain below 120 degrees (100 degrees; 90 degrees), to which 33% (22%; 17%) AM belongs, then p must remain below 0.436 (0.3653; 0.327).

5. THE DERIVATION OF THE CONTROL CURRENT-TIME FUNCTION

The PIN diode offering of German manufacturers is not large. Types which used to be offered for use in TV receivers have disappeared again from the market, now that other concepts are used in tuners. The types that are still easy to find - BA379, BAR79 and BAR15-01 (two diodes in one SMD package) - are suited for use on two metres without reservations. In the 70cm band I would recommend compensating

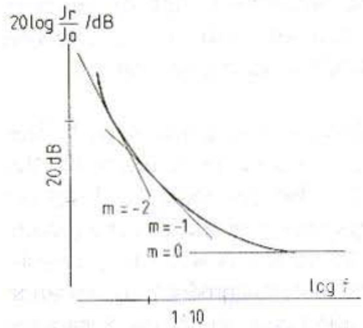


Fig.14: Typical course of an oscillator's sideband noise

for the diode's capacity, so as to get an isolation of around 25dB at zero current. Measurement of insertion loss in a 50Ω ohm system produces almost exactly the same curve (like Fig.10), from which the AC resistance (fig. 11) can be calculated.
The lowest AC resistance barely exceed 10Ω the insertion loss drops barely below 1dB. In this respect, then, PIN diodes are inferior to the switching diodes mentioned earlier. For this reason you should avoid complicated arrangements of several PIN diodes if high sensitivity is a requirement. The insertion loss (and increasing AM) degrade the noise figure of the receive system in well known ways. To try to cure this, you could use impedance transformations with pi and T arrangements of several diodes. These would require a complicated control generator with separate time functions for the transverse and longitudinal (''vertical'' and ''horizontal'') diodes.

I don't want to make it that complex here. Each individual antenna should have just one PIN diode in circuit, similar to Fig.10, to produce the same star arrangement as found in Rogers (3) and Zopp (4).

In Fig.11 an auxiliary straight line has been drawn in to illustrate the relationship <you type it!>. The curve of the diode coincides with this over a broad range of currents. So that equation (4) can now be valid, mixing must result between two diodes, so that

$$I_{D1}^{-0.85} \cdot I_{D2}^{-0.85} \sim (50\Omega)^2$$

The value of the proportionality constant still missing can be found if equal quantities are delivered by both sources, bearing in mind that by definition, AC resistance must equal 50Ω.
To this belongs a control current of around 0.65mA. Equation (5) then becomes

$$I_{D1} \cdot I_{D2} = (0.65\text{mA})^2 \qquad (6)$$

This control current function is illustrated in figure 12. In reality one would not take the control current to really large values but would let it end up between 5 and 10mA. We are still left with a variance between equation (5) and the actual diode curve. The control current function of Fig. 12 is thus a first approximation, albeit a good one. WE produce it in practice as a triangular form with an analogue function generator and optimise it in the final version by equalising the bends for best FM staircase form and smallest AM.

For all the diodes of a commutator we have the resulting control current functions seen in Fig.13. We must therefore either construct an eight-phase generator or divide the currents from a bi-phase generator with suitable switches of diodes of an even or odd number. If the control currents are correct, we will now find that the receiver has regained its selectivity.

6. THE CHOICE OF ROTATION FREQUENCY

The spectrum of Fig.6 does not hold for real Doppler signals, which look at best like Fig.9. It will contain further lines of higher frequency, produced by inequalities (k-rating) in the Doppler signal. If they go into the neighbouring channel, then the selectivity is corrupted. If you are not sure you have hit upon the best time function, you can reduce the problems further by dropping the rotation frequency n.

If n lies within the audio range, the intelligibility of speech will be degraded during direction finding. At the same time, any speech activity will interfere with direction finding. However, since you can get a usable bearing with just a few rotations, this can be don in the gaps between speech. A high n is an advantage then, as it allows more rotations over the same time. It is easy to imagine an automatic circuit that recognises pauses in conversation and carries out direction finding whilst blocking the audio path.

Intelligibility of transmitted speech does not require any components below 300 Hz. An n of less than 300 could thus be of use if bearings need to be taken during speech. A precondition to this is that the transmitting station does not produce any deviation in this audio frequency region. Separation of the Doppler signal from the audio on the receive side is easily achieved with commonplace filters.

In many transmit and receive oscillators the interference phase deviation increases significantly in the vicinity of the carrier. In contrast, the Doppler frequency deviation decreases with n. A lower boundary for n can be calculated like this at which the signal-to-noise separation in Doppler evaluation becomes behaviour of the sideband noise (fig. 14) or at least a measured value and the slope.

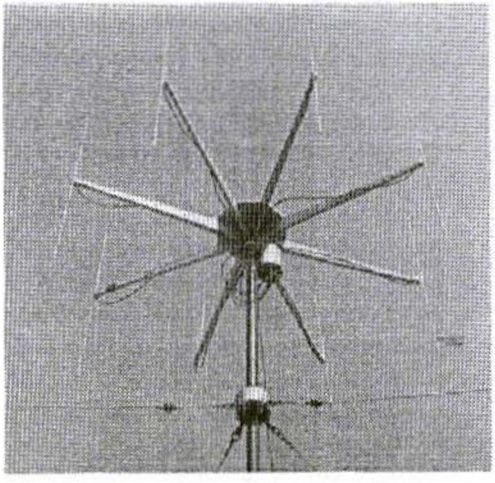


Fig.15: A circular group of eight dipoles on a mast

In general, the following is valid

$$\frac{J_r(f)}{J_o} = k_m \cdot f^m, \qquad (7)$$

in which J_r and J_0 are the Bessel coefficients, their relationship in dB being expressed by the sideband noise ratio, k is a constant and m is the slope of the curve at the desired frequency. In the vicinity of the carrier m will lie between 0 and -2; k_m is determined by a single measured value (e.g. $-80dB_c$ at 1 kHz, m = -2) and is measured in units of $Hz^{-(m + 1/2)}$. The total noise deviation in a bandwidth given by f_1 and f_2 is

$$\Delta F_r = 2 \cdot k_m \cdot \sqrt{\frac{1}{2m+3}\left(f_2^{2m+3} - f_1^{2m+3}\right)} \qquad (8)$$

This value can be put into relationship with the usable deviation by employing equation (1). For f_1 and f_2 suitable boundary limits should be established, which are produced from filtering the Doppler signal after demodulation. I select as an example $f_1 = 0.5 \cdot n$ and $f_2 = 1.5 \cdot n$ and $k_{-2} = 100Hz^{1.5}$, which corresponds to the example in the previous paragraph. Equation (8) simplifies itself to become

$$\Delta F_r = \frac{200/Hz^{1,5}}{\sqrt{n/Hz}}$$

If we now select p = 0.35, so that the Doppler deviation works out, according to equation (1), as ≈ 2 . n, then the signal-to-noise ratio amounts to

$$\frac{\Delta F}{\Delta F_r} \approx \frac{2 \cdot n \cdot \sqrt{n}}{200} = 10^{-2} \cdot n^{1,5}$$

If a $\Delta F/\Delta F_r$ of greater than 10 is required, then the following are valid: either $n^{1.5} > 1000$ or else $n > 1000^{0.667} = 100Hz$. If $\Delta F/\Delta F_r$ of greater than 100 is required, then we get under the same conditions n > 464 Hz.

Averaging over N rotations reduces, on statistical grounds, the influence of noise by a factor of $\sqrt{N}$. A broad field opens up here for digital signal processing (DSP).

Using high-end equipment we would use a second receiver chain with a fixed antenna in order to acquire a signal without Doppler component at the IF or audio level. That now makes available the speech modulation without the distortion, which can be subtracted from the mixed modulation to produce the pure Doppler signal.

A further calculation enables us to prove that direction finding in most cases gets by with a lower level of received signal than is necessary for intelligible speech. Since Doppler does not reduce transmission range, I shall spare myself this calculation.

Commercial direction finding equipment (5) operates with n = 150 to 170 Hz, for historical reasons. Early on, mechanically driven capacitive commutators were being used and this relatively low frequency was favourable to maintaining a separation from the speech band. It can be problematic when there are oscillators with relatively high levels of sideband noise in the complete set-up. An averaging of several rotations becomes necessary in order to maintain stable bearings.

7. PARTICULAR CHARACTERISTICS OF THE RECEIVE ANTENNA

The arrangement of eight dipoles, named the octopus by Rogers (3) and dubbed spontaneously the monkeys' merry-go-round by my wife, needs to be mechanically stable. The commutator should be put at the centre, not as shown in Fig.15 where it is causing asymmetry. The photo is only my first trial model, so I ask for your understanding. In any case, you learn from your mistakes which leads us to Fig.17 which clearly shows not only the inadequacies of this antenna but also of the filtering at that time.

The feeder cables from the dipoles to the commutator should have exactly equal lengths and be made from the same drum of cable. To avoid false coupling between the dipoles, we need to detune the unused ones. This is achieved in open half-wave dipoles by the high impedance at their connection point. The PIN diodes do this automatically if the feeder cable is a multiple of a half wavelength. There are other ways of doing the dimensioning but these involve multiple measurements, specific feeder lengths and defined values of p. For example you could do this by choosing the most suitable length of the cable to be equal to the radius of the antenna group. The feeder could then be built into the spoke. Air insulation is feasible and other changes to the cable brought about by stress, temperature, wind and ageing are eliminated. In the ideal case each dipole will behave as if it had no

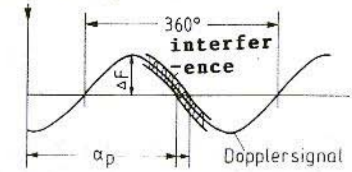


Fig.16: Derivation of display fluctuation through interference and noise

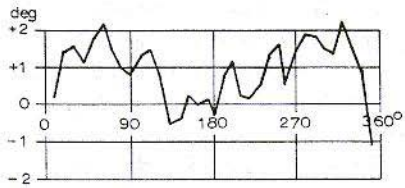
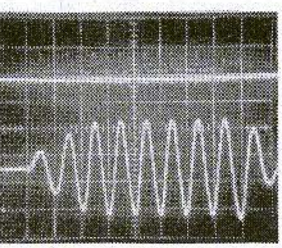


Fig.17: The azimuth-error diagram reveals insufficient filtering through rapid antennaasymmetry caused by slow periodicity



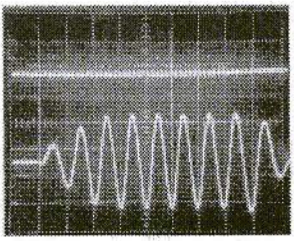


Fig.18: Control signals for the commutator (Y1) and build-up of the filtered Doppler signal (Y2) with mathematically positive (a) and negative (b) rotation. Y1: 5V per division; Y2: 1V per division; X: 2ms per division

affinity to the other seven. A certain degree of lopsidedness of the horizontal polar diagram is inevitable, and the mast must be responsible for this. If it lies below 3dB, the Doppler will work without problem, though.

8.
PROCESSING THE DOPPLER SIGNAL

The ΔF curve of Fig.9 is, as it is, unsuitable for determining the zero-pass point. Because of the unequal movement to an octagon harmonics are produced, which make for the formation of the staircase curve. These harmonics should be filtered out to the extent that the remaining fluctuations in the sine wave now produced lie below the desired resolution. Looking at Fig.16, we see it is designed to show how to approximate fluctuations in the display by the noise overlaid.

The Doppler (useful) signal has, at the zero-pass point, a slope of

$$\frac{d(\Delta F = 0)}{d\alpha} = \pm \frac{\pi}{180^\circ} \cdot \Delta F \qquad (9)$$

An overlaid interference voltage of magnitude ΔF_s causes a shift to the zero-pass by a maximum of

$$\Delta\alpha = \pm \frac{180^\circ}{\pi \cdot \Delta F} \cdot \Delta F_s \qquad (10)$$

Inadequate filtering of the harmonics leads to systematic bearing errors, which can be recognised by the periodicity in the azimuth error diagram (Fig.17). The same diagram also illustrates the errors which arise from geometric errors in the antenna group.

The noise deviation, which overlays the useful deviation, leads to statistically fluctuating displays. The largest deviation occurs when measuring a single rotation per display. Putting that into figures, assume we have in equation (10) the values of 0.1 and 0.01 for $\Delta F_s/\Delta F$, which were produced with rotation frequencies of 100 Hz and 464 Hz respectively. This gives $\Delta\alpha = 5.7^\circ$ or 0.57° respectively. The first result demands improvement, the second is acceptable. It proves that quite good direction finding can be achieved with one single rotation in 2.2ms.

The necessary filtering requires that the Doppler signal must first build up before it can be evaluated. This building up process is shown in Fig.18. At the beginning of rotation, noticeably at the timing pulse on the upper trace, the amplitude is growing to a value at which it remains. Here this is achieved after three rotations. Afterwards (in this example) four rotations are meas-

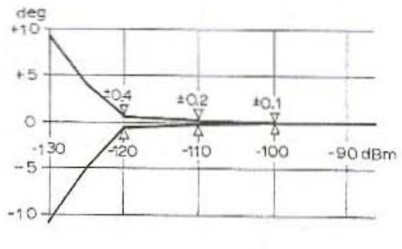


Fig.19: Noise induced display functions with dependency on the receiver's input signal strength

ured; one more is done as a check to see if the receiver is producing sufficient receive signal. After that the rotation is ended. This is just one example for many possibilities; according to individual requirements of measurement speed, broadband or narrowband filtering can be selected. The build-up time of a band filter is inversely proportional to its bandwidth, so a rapid indication calls for a broad filter (but these let in more noise and other interfering signals). Narrow filters require longer times (an order of magnitude of seconds when the bandwidth is of the order of Hz) but they suppress interfering signals of n varying frequencies better. Noise reduction is proportional to the root of the bandwidth reduction. The improvement of noise-influenced display fluctuations is therefore proportional to the root of the lengthening of the build-up period. The same result is produced by averaging out direction finding over several rotations, and following Shannon's information theory, we should not be expecting anything else.

For filtering the Doppler signal all possible active and passive filters can be brought into service. N-path switching filters, as used by Rogers (3) and Zopp (4), assume a special role. They are bandpasses which, because they use the same tempo of rotation, are always correctly in tune with n and can thus be made as narrow-band as wished.

A very narrowband system can possibly be made to work satisfactorily during simultaneous speech. I have not put this to the test. Any use of switched filters must be recognised as introducing the possibility of

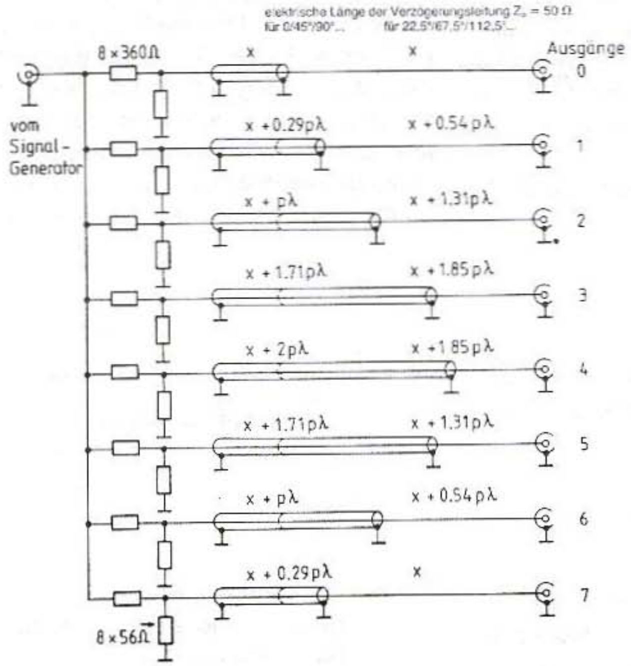


Fig.20: Circuit of the antenna simulator from phase lines of defined length

new ripple in the Doppler signal. They must always be followed then by conventional analogue filters, which will suppress the ripple.

In practice a mixture of bandpass filtering and averaging has proved itself. By way of example, a system (1) , working with n = 1000 Hz, built up in three rotations and averaged over ten rotations, gives noise-induced fluctuations in display shown in Fig.19. The input power -120dBm in this illustration corresponds to an RF signal-to-noise ratio of about 10dB; speech is just readable. Doppler direction finding on the other hand is error- free.

The various filtering in the IF and audio parts of the receiver influence transit time. A timing error arises between the control current for the reference dipole 0 and the corresponding result at the output of all the processing, and α_p is measured too large. A compensation can be made for this timing error by moving the antenna group or by all-pass networks in the signal path. The possibility remains of dependence on temperature or ageing (and filters going off-tune). An elegant solution to this problem is the use of anti-sense rotation. Other conditions remaining equal, the bearing value now consists of the timing between the Doppler signal's zero-pass in a positive direction and the reference point. With the transit time Δp will be measured too small. The average value of the measurements in both directions will no longer contain the transit time!

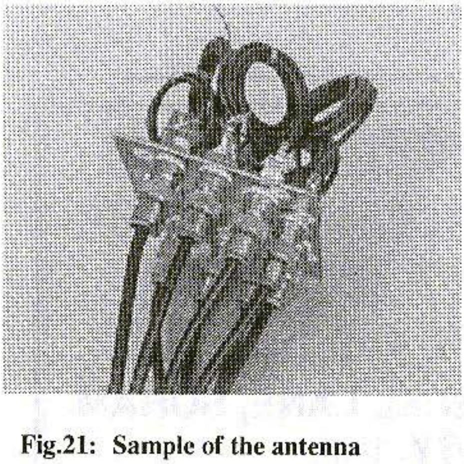


Fig.21: Sample of the antenna simulator

9. SOME DEVELOPMENT HELP

For testing a Doppler system it is better to rotate the antenna group and receive a fixed-location transmitter. This needs only have low power (-60dBm at 100 metres' distance). Then the wave of the propagation path is kept constant and will produce results that remain equal even in the case of multipath reception. A beacon transmitter of this kind can also be useful later on, because its bearing is indicated immediately if something in the set-up is altered. Recording azimuth error diagrams (Fig.17) involves going out into the great outdoors, which according to experience seems always tied up with tropical heat and unremitting sunshine or else Siberian cold and snowdrifts. All the same, a lot of other work, such as optimising the time function or the filtering, can be carried out under your own roof with the aid of an antenna simulator. It consists of a few bits of coaxial cable, which are connected between signal generator and commutator. Following the dimensions of Fig.20, it replaces a group of eight antennas, which receives just from the reference direction if

output 0 instead of antenna 0, output 1 instead of antenna 1 and so on are connected. Moving further one step alters the bearing each time by 45°. For intermediate values one must make the cables different lengths. The lengths for 22.5° are already given in Fig.20; x is a length which can be chosen freely as it turns out from the cabling. The voltage divider has 24dB attenuation and serves for the correct termination of the signal generator and commutator as well as decoupling the outputs from one another. A star-form set-up is offered; Fig.21 shows a constructed example. If you were to show it to Mr.Doppler, he would probably not connect it in any way with the effect bearing his name

10. LITERATURE

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